THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Ship Behaviour and Ship-Bridge Allision Analysis

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Abstract

The demand for maritime transport has increased with the growing demand for worldwide trade. This has led to a major increase in maritime traffic and ship sizes over the last decades, which raises the probability of accidents. The methods used in maritime risk assessments today are based on old hypotheses that do not include all data available today. The main objective of this thesis is to develop numerical models and methods for the analysis of what is considered as normal navigation behaviour at sea today and improve the analysis of probability for ship-bridge allisions.

The first part of the thesis describes what is considered as normal meeting distance at sea today. This information is later used while identifying failure events to ensure that the event behaviour was not caused by other ships. These few cases are excluded from the methodology since the communication and situational awareness in the situations are not known. However, while studying the probability of ship-bridge accidents, it is also important to understand how waterway restrictions may affect the probability of ship-ship collisions. Therefore, this thesis also includes a study of how the improved knowledge concerning meeting distance could be used in a near ship-ship collision identification model. One of the main findings considering normal meeting distance is that small and large ships meet each other at a similar distance at sea.

In the second part of the thesis, a methodology is proposed to estimate the probability of ship-bridge allision. The presented methodology uses Automatic Identification System (AIS) data and a ship manoeuvring simulator to simulate and analyse marine traffic with regards to risks for accidents, such as ship-bridge allisions. A failure event identification method is also presented, which is needed to determine the frequency, duration and behaviour for the accident scenarios. The three events that were modelled and simulated in the simulator were: *drifting ship*, *sharp turning ship* and *missing turning point*. The probability of the different failure events corresponded to previous statistics confirming the AIS-based methodology. This means the methods to obtain the probability and duration of the failure events could be utilised in other areas. The simulation methodology was confirmed with the probability of grounding in the Great Belt VTS area.

This thesis firstly contributes to a better understanding of the modelling of probability for ship-bridge allisions. This will support bridge-building engineers who need to take into account accidental loads from ship-bridge allision while designing bridges. Secondly, this thesis also contributes to a better representation of normal behaviour at sea, which is used both in fairway designs and in estimations of ship-ship collisions.

Keywords: AIS data, failure statistics, risk modelling, ship domain and ship simulations.

Preface

This thesis is comprised of the research work carried out at SSPA Sweden AB and the Division of Marine Technology, Department of Mechanics and Maritime Sciences at the Chalmers University of Technology during the years 2017 to 2020. Financial support for this research was provided by the EU Interreg ÖKS project MARIA, Vinnova, Norwegian Public Road Administration, Logistik och Transportstifelsen and Hugo Hammars Fund.

I would like to express my gratitude to my examiner and head supervisor, Professor Jonas W Ringsberg, for all feedback and his dedication to improving my skills. I also want to thank my assistant supervisor, Dr Martin Svanberg, for the feedback and especially pointing me in a correct direction early in the journey.

I am also very grateful to my colleagues at SSPA for their support, Björn Forsman and Erland Wilske for your support from my first days at SSPA; former colleague Henrik Holm, who taught me SQL and how to handle AIS data; and former colleague Fredrik Olsson for the support getting the simulations to run. Further, I would like to thank my friend Erik Iveroth, who taught me the programming language Python, which I have used throughout my research.

I could never have done this without the unconditional love and support from my family. I am especially thankful to my amazing wife, Erica Hörteborn.

Axel Hörteborn
Varberg, December 2020

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List of appended papers

For each of the three appended papers, the author of this thesis contributed to the ideas presented, planned the paper with the co-authors, performed the numerical simulations, and wrote the manuscript together with the co-authors.

Paper I Hörteborn, A., Ringsberg, J.W., Svanberg, M. & Holm, H. (2019). A revisit of the definition of the ship domain based on AIS analysis. Journal of Navigation, 72(3), pp. 777-794. doi:10.1017/S0373463318000978.

Paper II Hörteborn, A., Ringsberg, J.W. & Svanberg, M. (2019). A comparison of two definitions of ship domain for analysing near ship–ship collisions. In Developments in the Collision and Grounding of Ships and Offshore Structures: Proceedings of the 8th International Conference on Collision and Grounding of Ships and Offshore Structures (ICCGS 2019), 21-23 October 2019, Lisbon, Portugal, pp. 308-316, CRC Press, Leiden, The Netherlands.

Paper III Hörteborn, A. & Ringsberg, J.W. (2020). A method for risk analysis of ship collisions with stationary infrastructure using AIS data and a ship manoeuvring simulator. Submitted to the journal Ocean Engineering (under review).

List of other published papers by the author

Paper A Svanberg, M., Santén, V., Hörteborn, A., Holm, H. & Finnsgård, C. (2019). AIS in maritime research. Marine Policy, 106, p.103520.

Paper B Andersson, A. (NKA Hörteborn A.), Forsman, B. & Wilske, E. (2016). Estimation of ship bridge collision probability by use of Monte Carlo simulations. Challenges in Design and Construction of an Innovative and Sustainable Built Environment: IABSE Congress, 21-23 September 2016, Stockholm, Sweden (pp. 142-149), IABSE - International Association for Bridge and Structural Engineering, Zürich, Switzerland. ISBN: 978-3-85748-144-4.

Nomenclature

Greek notations

θ	Bearing [degrees]
ι	Location
λ	Scale [-]
μ	Mean value
σ	Standard deviation [-]

Latin notations

AF	Annual frequency of bridge element collapse
E	Allision energy [J]
F_{dyn}	The impact force of the allision in the Eurocode [J]
i	Index denoting type of event [-]
j	Index denoting ship type [-]
k	Constant in VCRO model [-], or index for a ship route in Paper III [-]
L	Ship length [nautical miles: nm]
l_θ	The length of the ship domain along the bearing to the second ship [nm]
M	Displacement [kg]
m_n	Ship's manoeuvrability coefficients [-]
N	The number of candidates [-]
n	The traffic intensity in the Eurocode [ships/hour], or index in the VCRO model [-]
N_{Col}	The number of accidents [-]
$N_{Cat,j,k}$	The estimated number of ships per year for ship type *j* on a route *k* in the area [-]
N_{SIM}	The number of simulations for event *i* [-]
$N_{T,j,k}$	The number of turns the ship *j* makes on its route *k* [-]
p_a	A factor of human intervention in the Eurocode [-]
PA	The probability of vessel aberrancy in AASHTO [event/hour]
PC	The probability of collapse due to a bridge allision in AASHTO [event/allision]
P_C	The failure probability in the Eurocode and in Eq. (2.1) [failure/hour]
$P_{CSA,i}$	Probability that a ship misses a turn [1/turn]
PF	Adjustment factor to compensate for potential mitigations in AASHTO [-]
PG	The geometric probability in AASHTO [vessels/hour]
$P_{ft,i}$	The event probability per hour for the event *i* [1/hour]
R	Length of half major axis of ellipse [nm], or resistance in the Eurocode [J]
S	Length of half minor axis of ellipse [nm]
$t_{N,j,k}$	The average time ship type *j* sails on the route *k* [hours]
v	Velocity [m/s]
x	Position of where the failure occurs in Eurocode [m], or distance between ships in the VCRO model [nm]
X_θ	Distance between ships in bearing [nm]
Y	Speed differentiation [m/s]
Y_r	Number of repetitions of one-year's traffic represented [-]
z	Phase [degrees]

Abbreviations

AIS	Automatic Identification System
APF	Artificial Potential Field
COG	Course Over Ground
DMTS	Dynamic Maritime Traffic Simulator
DOF	Degrease of Freedom
FSA	Formal Safety Assessment
GWP	Global Warming Potential
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
IMO	International Maritime Organization
MDTC	Minimum Distance To Collision
MTS	Maritime Transportation System
nm	nautical mile
NMEA	National Marine Electronics Association
NPRA	Norwegian Public Road Administration
SFT	Submerged Floating Tunnel
SOG	Speed Over Ground
SQL	Structured Query Language
TLP	Tension Leg Platform
TSS	Traffic Separation Schema
VCRO	Vessel Conflict Ranking Operator
VTS	Vessel Traffic Service

1 Introduction

The increase in marine traffic density and ship sizes over the last decades has raised the potential threat to existing maritime infrastructure. At the same time, the advancement in bridge-building engineering has created new opportunities to build larger bridges that span over wider waterways. However, building bridges over wide waterways tightens the free sailing width in the waterway, which may increase the risk of ship-ship collisions. The increased threat to existing bridges and new building of larger bridges demands new methods and models that can be used in risk assessments of ship-ship collisions and ship-structure allisions in fairways.

In this thesis, the accident between ship-structure is differentiated from ship-ship, where the former is denoted as allision and the latter as collision. This differentiation separates ship striking another ship and ship striking a stationary object. The following subchapters provide background and motivation for this research within the fields of the ship-ship collisions and ship-structure allisions.

1.1 Background and motivation

Risk analysis is used to ensure that the bridge design and waterway traffic fulfil the expected safety standards. Despite this, 34 major bridge collapses caused by ship-bridge allisions occurred from 1960 to 2007, which resulted in the loss of more than 340 lives (AASHTO, 2009). The worst ship-bridge allision to occur in Sweden is the 1980 Almö bridge accident, in which MS Star Clipper had a manoeuvring problem and hit the Almö bridge. Due to fog and lack of emergency routines seven cars drove off the broken bridge, and eight people died. The risk of ship-bridge allision was not included in the design criteria for the construction of Almö bridge. The Eurocode 1 now requires that this risk is included in the design (CEN, 2006). Ship allision is one of the most important load cases for the design of these bridges, according to Hauge et al. (1998). Bjørndal et al. (2016) makes a similar claim regarding the Bjørnafjord crossing in Norway and states that in addition to environmental and service loads that form the basis of the strength design of a bridge, the accidental probability of various hazardous events and accidental loads must be considered.

Reliable infrastructure is a key to the economic growth of the last century; the road network has expanded vastly all over the globe and involves numerous bridges. However, building bridges is expensive; to give two examples, the building costs of the Öresund bridge and the Great Belt bridges in the late 1990s were approximately 3 billion Euros each (Great Belt Fixed Link, 2020; Öresund Bridge, 2020). The cost of rebuilding one of these bridges, after a ship destroying it in a bridge allision, would probably exceed the building cost. Minor accidents, only damaging the bridge, might also be costly and in some cases are the repair cost exceeded by the socio-economic cost of detours and delays. The socio-economic cost estimations are rough and seldom published, but to give one example: a lorry hit the Södertälje bridge in 2016; the repair cost was estimated to 2 million Euros (DI, 2016), and the socio-economic cost of the accident was estimated to 7.5 million Euros (Schmidt, 2016). Another bridge accident that was studied from a socio-economic perspective was the collapse of the I-35W bridge in Minnesota (US), where structural failures caused the bridge to collapse in 2007. The socio-economic cost was estimated at \$165 million, and the building cost was estimated at \$234 million (Haugen, 2008). These examples illustrate that the cost of allisions could be severe. Despite this, Hauge et al. (1998) claim that excessive conservatism should be avoided, in connection to protecting from ship-bridge allisions, since extra protections have severe cost impacts in bridge-building.

Both collision and allision accidents also have a major impact on the environment. In both types of accidents, there is a risk of oil leakage and/or pollution from the cargo damaging the local marine environment. The worst collision, from an environmental perspective, dates back to 1979 when SS Atlantic Empress and the Aegean Captain collided and almost 3 million tons of oil leaked. A more recent example is the January 2018 Sanchi and CF Crystal collision in the East China Sea 6, where Sanshi sank with 136,000 tonnes of crude oil (IHS Fairplay, 2020). Furthermore, repairs and new building also have a negative impact on the environment. For example, the building process and material for a 225-metre cargo ship have a Global Warming Potential, GWP, of 47.9 million kg CO_2-equivalents (Quang et al., 2020). Du et al. (2014) studied five different bridge concepts for a 338-metre long bridge in a Life Cycle Analysis perspective, and all alternatives had an estimated GWP of roughly 6 million kg CO_2-equivalents.

The research presented in this thesis was initiated by the Norwegian E39 project, which aims to make a continuous coastal highway route between Kristiansand and Trondheim in Norway. Today, this route includes seven fjord crossings with ferries, and with a continuous connection, the Norwegian Public Road Administration (NPRA) aims to reduce the travelling time by more than 50 percent (NPRA, 2020). The crossing of Bjørnafjorden is one of the most challenging parts of the project. The fjord crossing is just over 5 km wide, and the fjord has a depth of over 500 metres. Initially, three different crossing solutions were investigated; a tension leg platform (TLP) bridge, a submerged floating tunnel (SFT) and a floating bridge (Bjøndal et al., 2016). Analysing the risk of ship-structure allisions for these concepts required new and innovative models and methods. Adding a bridge will shrink the fairway width; therefore, it is also important to understand how this affects the probability of ship-ship collisions.

Even though many researchers have already covered this field, there are still improvements to be made (Pedersen, 1995; Friis-Hansen et al., 2008; Goerlandt and Kujala, 2011; van Dorp and Merrick, 2011; Rasmussen et al., 2012). This is a broad research field, including both probability and consequence assessments for multiple types of accidents. Research concerning the consequence side of ship-structure allision has improved significantly over the last decades (Sha et al., 2019). However, limited research has focused on the probability of allisions and determining which ship to include in the consequence analysis. Projects such as the fjord crossings in the Norwegian E39 project require a better understanding of the probability of ship-bridge collisions and what ship to use in extensive structural assessments.

Risk assessment methods for collisions and allisions in shipping build on the theory that Fujii and Shiobara (1971), Fujii and Tanaka (1971) and Macduff (1974) pioneered and established in the early 1970s. At that time, ship movements were often estimated based on records of radar images. The introduction of Automatic Identification System (AIS) in the early 2000s and availability of AIS recordings have since then, according to Svanberg et al. (2019), resulted in new possibilities to enhance the accuracy in maritime risk assessments. The research in this thesis utilises the AIS data and the increased computer capacity in new innovative methodologies to estimate the probability of maritime accidents.

1.2 Objective

The objective of this thesis is to contribute to safer ship navigation in fairways by the development of numerical models and methods for analysis of what is considered as normal navigation behaviour at sea today, and analysis of the probability of ship-bridge allisions. Three research questions are addressed in the thesis:

- How do ships navigate at sea today? The framework for risk assessment was introduced 50 years ago; is ship behaviour similar today?
- How can failure events of ships sailing in fairways be identified and quantified with respect to frequency and duration?
- How does the probability and duration of failure events influence the probability of allision and the design criterion for maritime structures?

Based on the main objective of the thesis, and by considering the three research questions, four goals for the research in the thesis were formulated.

(i) Propose a new methodology for defining the ship domain based on current local characteristics.
(ii) Develop methods that can identify and quantify failure events for ships navigating in fairways.
(iii) Propose a methodology that uses failure events and AIS data in a ship manoeuvre simulator to estimate design loads on maritime infrastructure.
(iv) Apart from estimation of the design load on maritime infrastructure, determine whether the simulation methodology also enables new and innovative possibilities to analyse risk mitigation options.

1.3 Limitations

The revisit to the ship domain presented in Paper I is limited to a study of the normal behaviour at sea today. The method to obtain the ship domain does not evaluate whether or not it is safe to use this domain; instead, it resembles the navigation behaviour at sea today.

The simulations presented in the thesis are restricted to the simulation of only one ship at a time, i.e., two ships are not simulated at the same time. This is since the number of possible actions a captain can make in situations with event failures on multiple ships are too many and too complex to address in a fast-time manoeuvring simulator. This is one important differentiation and limitation compared to other methods where a ship colliding after avoiding another ship is a separate accident event.

The risk of ship-bridge allisions is evaluated with the simulation methodology proposed in Paper III. However, the consequence analysis of allisions is limited to the estimation of the kinetic energy just prior to the allision. The consequence, such as structural integrity and damaged caused to the ship or damaged bridge after an allision event, is completely outside the scope of this thesis.

The methodology for estimation of the probability of ship-bridge allision is verified with the probability of ship grounding. It would be preferable, from the model-developing perspective, to verify the model with allision accidents, but there have not been enough allision events for comparison.

1.4 Outline of the thesis

The structure of the thesis is as follows: Chapter 2 presents an overview of existing methods for allision and collision risk assessments. Chapter 3 presents the methods used in the thesis, together with their assumptions. Chapter 4 presents a brief summary of the results presented in the three appended papers. The conclusions are presented in Chapter 5, followed by suggestions for future work in Chapter 6.

2 Review of studies on ship allisions and collisions

The chapter presents an overview of methods used in estimations of probability for ship-bridge allisions, ship simulation methods and ship-ship collisions. Common for the included methods in this chapter is that they focus primarily on the probability of occurrence and not the consequence in the risk analysis. Most models in this field that focus on probability are based on the equation that Fujii and Shiobara (1971) and Macduff (1974) proposed in Eq. (2.1):

$$N_{Col} = N \times P_C \tag{2.1}$$

where N_{Col} in is the number of accidents, N is the number of candidates and P_C is the causation probability, which is composed of environmental factors, mechanical failures and human error. Chapter 2.1 presents an overview of methods defining the ship domain and uses of it. Chapter 2.2 presents an overview of simulation methods. Building codes are central in civil engineering and bridge-building. Thus, Chapter 2.3 presents the two major building codes and an extended method to obtain the probability of allision.

2.1 Methods using the ship domain concept

The term “ship domain” was first defined by Goodwin (1975) as the effective area around a ship which a navigator would like to keep free with respect to other ships and stationary objects. Within the same field of research, Fujii and Tanaka (1971) had introduced the term “effective domain” four years earlier while modelling the traffic capacity. They defined their domain as the effective domain around a ship into which other ships avoid entering. Pietrzykowski and Uriasz (2009) investigated different types of ship domains. They identified that it is difficult to differentiate if the ship domain is the area navigators want to keep clear, like the definition by Goodwin, or if it is the area that is left clear, like the domain by Fujii and Tanaka. It may also be differentiated into it being a difference between how much space the navigators want to have versus how much the navigators get. This field of research is 50 years old, and new technology like the AIS may have altered the way navigators operate. The early research on ship domains used radar observations, and the introduction of AIS enables new types of studies. In this subchapter, known gaps in the ship domain research are highlighted and a few different use cases are presented.

Gucma and Marcjan (2012) used AIS data to study if the type of ship and encounter type affected the ship domain in the Gulf of Pomerania. They concluded that the type of ship had no effect on the shape of the domain, and only minor differences could be observed with different types. Hansen et al. (2013) investigated the passing distance between ships in the Great Belt and the Drogden Channel. The distance to target ships was measured in ship length, and it was determined that the domain had the same shape and size as the effective domain by Fujii and Tanaka (1971). In the study by Hansen et al. (2013), it was assumed that the ship domain should be measured in the unit ship length; however, the study did not investigate if this was the actual case. According to Szlapczynski and Szlapczynska (2017), the ship domain has been defined by many others since it was introduced. The ship domain has also been used in different contexts ever since it was introduced; three of these could be summarised into traffic capacity, risk assessments and active risk mitigation.

The title of Fujii and Tanaka’s (1971) article was “Traffic Capacity”, which also summarises one area of research where the ship domain is used. In this research area, the ship domain is used to define the maximum traffic volume that can safely pass a specific width, sailing under bridges or within TSS’s (e.g. Frandsen et al., 1991; Jensen et al., 2013; Liu et al., 2016).

Another context where researchers have used the ship domain is in collision risk analysis. Goerlandt and Kujala (2014) compared the fuzzy logic model by Qu et al. (2011), blind navigation with a Dynamic Maritime Traffic Simulator (DMTS) without using any ship domain (Goerlandt and Kujala, 2011) and counting the number of ship domain violations with the method by Weng et al. (2012). They concluded that only modest claims could be made regarding the reliability of the risk estimate in terms of probability accuracy. Goerlandt and Kujala (2014) finally concluded that there is a need for a more valid method, with less uncertainty, that links ship-ship encounters to collision risk. Zhang et al. (2015) introduced the Vessel Conflict Ranking Operator (VCRO) model as another approach to identify near-miss situations. This model was updated with the Minimum Distance to Collision (MDTC) model and ship domain in Zhang et al. (2016, 2017). The MDTC is a model by Montewka et al. (2012) that identifies collision candidates depending on the ships' intersection angle and lengths. The MDTC model improves the collision diameter that Preben (1995) introduced while taking the ships' manoeuvrability into account when assessing situations.

The ship domain concept is also used in real-time manoeuvring, both for alert systems and autonomic shipping (Rong et al., 2015; Im and Luong, 2019; Zhang and Meng, 2019; Huang et al., 2020; Du et al., 2020). However, applying the ship domain in real-time collision avoidance may be controversial, since the ship domain is often a result of successful collision avoidance, as pointed out by Montewka et al. (2020). This is supported by Rawson and Brito (2020), who studied collisions and used the ship domain by Wang (2010) to study the number of encounters. In their study, they concluded that the statistical relationship between areas with a high number of encounters and number of collisions is weak. The research by Shen et al. (2019) tried to omit this problem and used a ship domain by Smierzchalski (2005), that takes the ship length and speed into account. This may solve some problems, but as Hansen et al. (2013) pointed out, navigators want to have a different amount of "free water" depending on the geography, a factor not accounted for in the ship domain by Smierzchalski (2005).

To summarise, since the ship domain is used in different types of applications, there is a need for different types of ship domains. For assessments of the probability of ship-ship collision and to study the effect of a shrinking water width, it is important to have a ship domain that represents how ships interact today. Gucma and Marcjan (2012) concluded that it is important to investigate how the ship domain relates to the ship size, whereas Hansen et al. (2013) concluded that ship domain by Fujii and Tanaka (1971) was correct in one location but not in another. Hansen et al. (2013) argued that it is thus important to investigate ship domains in multiple locations and types of water. There seems to be a need for a new method that revisits the ship domain, utilizing the AIS data, to obtain location-specific ship domains.

2.2 Simulation models used in maritime risk assessment

Computer-based simulation models have been used in the maritime field for decades. One example is Källström and Ramzan (1985), who used a combination of simulation models and model tests for the installation of the world's first commercial TLP. Nowadays, there are various types of maritime simulation models and software for different purposes. The models included in this chapter are an overview of three types of models: The Maritime Transportation System (MTS) model, autonomic ship simulators and ship manoeuvre simulators.

The MTS model handles the ships' temporospatial positions in a time domain-simulation, and the ships are moved according to their assumed speed and course. In this type of simulator, the hydrodynamic forces are not calculated, which makes it relatively fast and simple to use. This type of simulator was used by Ulusçu et al. (2009), who studied the risk of accident in the Strait of Istanbul. The model includes multiple parameters concerning the traffic and its prerequisites. In Ulusçu et al. (2009), these were obtained from the VTS, local operators' websites and hydrological institute. They split the Strait of Istanbul into 21 slices and analysed the risk of collision, grounding, ramming, sinking and fire/explosion. The risk profile in Ulusçu et al. (2009) was obtained using 25 repetitions of one-year's traffic; they concluded that the repetitions were good to capture rare events. Van Dorp and Merrick (2011) proposed using the MTS model for risk assessments in coastal areas. In this model, the traffic was simulated on routes, obtained from AIS data, and the ship failures and errors in the model were simulated based on expert opinions. The MTS model uses the HAZMAT (1997) wind drifting model for drifting events. Van Dorp and Merrick (2011) concluded that their model is good for comparison studies, but due to simplifications, they concentrated less on the absolute values. Goerlandt and Kujala (2011) continued this research and implemented the DMTS model. This simulator is also based on AIS data, but it addresses the meeting situations differently than the others. Goerlandt and Kujala (2011) used a Monte Carlo method to estimate the risk of collision and grounding in the Gulf of Finland. In this research the failure modelling was based on causation factors. Connected to this work is the research by Hänninen and Kujala (2010, 2012) who improved the research on causation factors using Bayesian networks. They concluded that the concept of causation probability is vague and there is a need for a more general probabilistic model. Rasmusen et al. (2012) used the ShipRisk software to quantify the risk to ship traffic in the Fehmarnbelt fixed link project. The ShipRisk software seems to be a mixture of the models by Pedersen (1995) and an MTS simulator by Ulusçu et al. (2009). In Rasmusen et al. (2012), the probability of human error, loss of propulsion and steering machine failure were analysed.

Another type of simulator is those aiming to enable autonomous navigation and voyage planning. These types of simulators are a bit more complex than the MTS models, since they include hydrodynamic forces in two dimensions. Xue et al. (2011) used a three-degrees-of-freedom (DOF) simulator, a potential field method and automatic collision avoidance for autonomous route finding. This simulator simulated the movements in surge, sway and yaw (see Figure 1). Xue et al. (2011) highlighted that there were some difficulties in implementing the potential field method without getting oscillations in tight situations. Despite this limitation, they concluded that the methodology appears to be well-suited for automatic route finding, which also handles collision avoidance. However, there still is much work required to integrate the knowledge of experienced mariners into the system before it resembles human navigation. Johansen et al. (2016) continued this research and added wind and currents to the model. By simulating different situations, they illustrated that their method could be tuned to acceptable control behaviours for a wide range of cases. Shen et al. (2019) continued this research and implemented a deep Q-learning model to comprehend automatic collision avoidance for multiple ships. In addition to the proposed algorithm model tests were also included in this research, running three self-propelled ships in a basin, to validate the mathematical model. Shen et al. (2019) concluded that the model tests and mathematical model gave similar results and recommended continuing with only the mathematical models. However, they also concluded that more parameters, such as speed derivatives, need to be included for realistic applications.

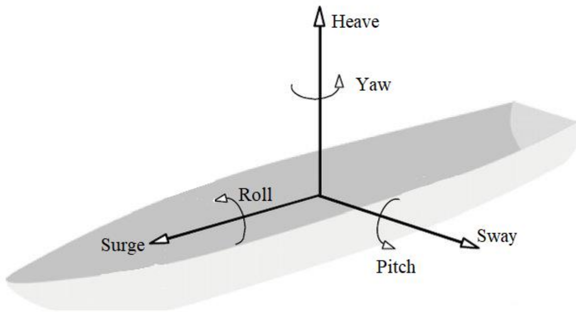

Figure 1. Illustration of a ship's six degrees of freedom.

Ship manoeuvring simulators are often used in extensive training, as manoeuvring in confined waters and ports is a complex issue. These types of simulators focus on accurate hydrodynamic modelling in six DOF (see Figure 1) to ensure the correct ship behaviour during training. Although the main use of manoeuvring simulators is training, it is an important tool while assessing risks in ports and fairways. Manoeuvring simulations are often used to decide operational limits, e.g. how many tugs a birthing ship requires in various wind conditions (Chen et al., 2018). Schaub et al. (2019) proved that the RAPID method, included in the SAMMON software (Baldauf and Benedict, 2018), had clear benefits for lecturing and training while improving ship handling. Weber et al. (2019) used the web version of Seaman, Seaman Online^{TM} (SSPA, 2020), and concluded that the simulator supports students in understanding the complexity of ship behaviours in different conditions. There are multiple providers of ship manoeuvring simulators; examples include full mission simulators from Transas, Kongsberg and Rheinmetall connected in the European Maritime Simulator Network during the Sea Traffic Management project (Poschmann and Wilko, 2017).

To summarise, the different types of simulation models and software have different pros and cons. In both the MTS and DMTS models, there are several types of failures/errors implemented, but the details on how these behaviours are implemented, their frequency and their durations are not clear. The MTS and DMTS models are fast to run, but they are not based on hydrodynamic force calculations, which limits the models' accuracy in scenarios with alterations of the ship's path. The simulation models used in autonomous navigation are based on more advanced hydrodynamic models, which enables better possibilities to alter scenarios, etc. However, the models in this category lacked implementation of human error and technical failures. Regarding the full mission simulators, Chen et al. (2018) highlight that a drawback with them is the cost since it is often very expensive to run simulations in full mission. Another drawback of these simulators is that they are time-consuming; the manoeuvring needs to occur in real-time, making it difficult to test thousands or millions of cases. In this thesis, a new methodology was developed, using the strength of these existing models to simulate real-world ship traffic, including location-specific failure events.

2.3 Bridge building codes and calculation of probability of allision

Two major associations, the Eurocode (CEN, 2006) and the American Association of State Highway and Transportation (AASHTO, 2009), define building codes applied in bridge-building. Both include equations for assessing the accidental load from ship-bridge allisions. The Eurocode influences the building codes of European countries with respect to the construction of bridges and proposes Eq. (2.2) for estimation of the probability that a ship will demolish a bridge (CEN, 2006).

$$P_f(T) = n \times P_C \times T(1 - p_a) \int_0^{\infty} P\{F_{dyn}(x) > R\} dx \tag{2.2}$$

where $P_f(T)$ is the probability of bridge collapse during the reference period T, n is the traffic intensity, P_C is the failure probability, p_a is a factor of human intervention, x is the position of where the failure can occur and is integrated over the area in front of the bridge, F_{dyn} is the impact force of the allision, and R is the resistance of the structure. AASHTO (2009) proposes a similar equation in Eq. (2.3).

$$AF = N \times PA \times PG \times PC \times PF \tag{2.3}$$

where AF is equal to $P_f(T)$, N is the number of vessels classified in different categories, PA is the probability of vessel aberrancy, PG is the geometric probability, PC is the probability of collapse due to a bridge allision, and PF is an adjustment factor to compensate for potential mitigations. These codes are primarily developed and applied for inland waterways with ship traffic in narrow waterways. One problem with these codes is that there is limited guidance in how to use them for bridges spanning over open waters. To obtain the probability of allision in these types of waters, the model by Pedersen (1995) and IWRAP software (Engberg, 2017; Friis-Hansen et al., 2008) is often used.

Pedersen (1995) studied the risk of grounding, allision and collision. Four accident categories were proposed to obtain the number of candidates, and the use of fault tree methodology was proposed to investigate the causation factor. The four accident categories could be summarised into:

1. Ships that follow the intended route but with a too-large offset from the centre of the route.
2. Ships that fail to turn at a given turning point.
3. Ships that make evasive actions due to other ships and thereafter colliding.
4. Other types of accidents, e.g. off-course ships and drifting ships.

Chen et al. (2019) reviewed models used in maritime risk assessments and concluded that Pedersen's model has been the basis of many risk assessment methods since it was first presented. One model that to a large extent builds upon Pedersen's equations is the IWRAP software (Friis-Hansen et al., 2008). This is a software from the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) that is encouraged by the International Maritime Organization (IMO) for quantitative risk assessments (IMO, 2010). IWRAP can be used to assess multiple types of risks, including collisions, grounding and allisions. The software has been used in multiple studies, e.g. in Cucunotta et al. (2017), who used IWRAP to compare the effect of using Vessel Traffic Service (VTS) versus not using VTS, and Ylitalo (2010), who studied the risk of accidents in the Gulf of Finland with IWRAP. Both concluded that the software yielded a similar result compared to the accident statistics. However, Ylitalo (2010) also concluded that the result was sensitive to the causation parameters, how the user defined the routes and the parameter *mean time between checks*.

In summary, the building codes ensure that the accidental loads are included in the design criteria of bridges. For more advanced constructions, the equations by Pedersen (1995) are often used. However, the codes are not developed for offshore bridges, and Pedersen's equations are sensitive to the input parameters. Further, none of them include AIS data, which, according to Svanberg et al. (2019), enables new possibilities for maritime risk assessments.

3 Methodology

The methods described in this chapter aim to mitigate the identified shortcomings of the ship domain, ship-ship collision assessments and the probability assessment of ship-bridge allisions. Papers I and II focus on the ship domain and ship-ship collision, whereas Paper III focuses on ship-bridge allision. The main results and conclusions from the papers are presented in Chapter 4. Figure 2 shows the connections between the papers.

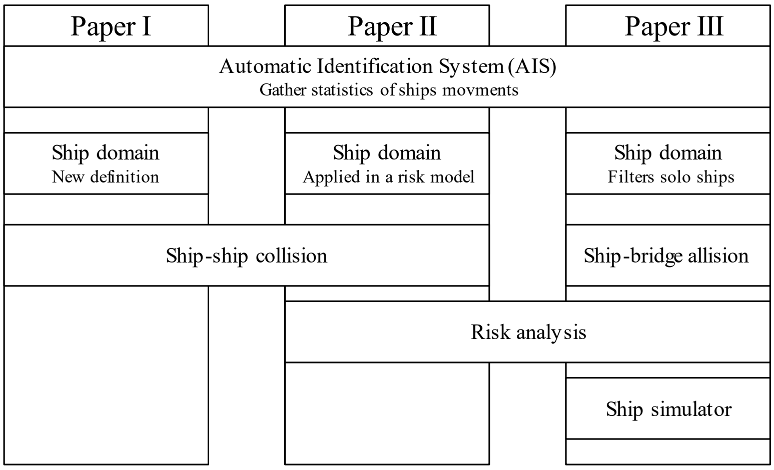

Figure 2. Connections between Papers I to III appended to the thesis.

AIS data contains information on how ships have travelled, and by comparing all the ships that pass an area, it is possible to distinguish between normal and abnormal behaviour. Information on both the normal and the abnormal behaviour is an important input to the three papers, as illustrated in Figure 2. The following subchapter describes the benefits of AIS data and how the data has been utilised in the research presented in the thesis and appended papers.

As described in the previous chapter, there are several areas of applications for the ship domain, and the methodology presented in Chapter 3.2 revisits the definition for the ship domain in the aspect of what distances are used at sea today. The ship domain is primarily used in ship-ship collision analysis, and the methodology in Chapter 3.3 describes how the revisited ship domain is implemented in the VCRO model.

The ship domain was revisited in Paper I, which enabled the study on ship-ship collision in Paper II. Paper III focuses on single-ship manoeuvring in simulations connected to ship-bridge allisions, where the ship is experiencing some type of failure event. It was discovered in literature studies that there was not enough research available to implement simulations of failures in situations where multiple ships were present at the same time. For this reason, all situations with intrusions of the ship domain (defined in Paper I) by a secondary ship were excluded from the analysis in Paper III.

3.1 The use of AIS data

The introduction and availability of AIS recordings have, according to Svanberg et al. (2019), resulted in new possibilities to enhance the accuracy in maritime risk assessments. The foundation for the research in the included papers is to a large extent based on AIS data. Since its introduction in 2002, ships larger than 300 gross tonnes must have an AIS transponder and transmit messages. AIS messages are separated into two types: position report and metadata message (Raymond, 2019). Every ship issues a position report every 2 to 10 seconds at sea, depending on the ship's speed and turning rate, and a metadata message every 6 minutes (ITU-R, 2014).

One limitation of AIS data is that it only includes temporospatial related data, and not information regarding the machinery status onboard or the verbal communication between ships' bridges, etc. Most of this data is recorded; however, it is stored locally onboard the ship in the voyage data recorder. The benefit of AIS data is that it always broadcasts to whoever is listening. This enables enhanced possibilities to study ship traffic over an extensive area and during a long period. This is a big difference compared to when Fujii and Tanaka (1971) studied the ship domain by radar images.

In this thesis, the position message has been used as both "single points" and "trajectories". The latter is obtained by combining multiple points into lines, and this is exemplified in Figure 3, where twelve AIS position reports are combined into 3 lines. The lines represent AIS messages with similar speed over ground (SOG) and course over ground (COG). In the figure, the red and blue lines have the same COG, but the SOG differs, and the green line to the right represents messages with a different COG and SOG. This method of combining messages has several benefits: the amount of data stored in the database is reduced; missing data points might not cause inconsistencies; a similar method is presented in Zhao and Shi (2019) and Wei et al. (2020).

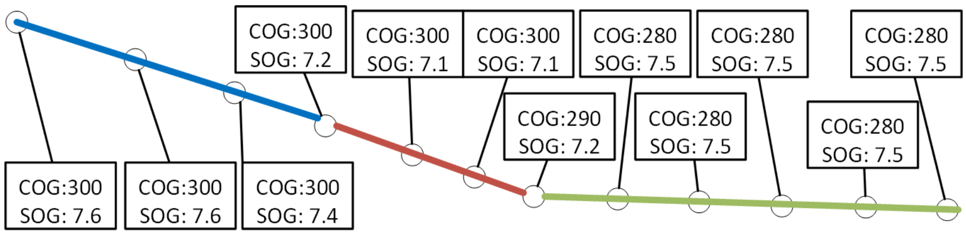

Figure 3. Illustration of how AIS position reports are converted to trajectories. The blue line represents AIS messages with COG: 300° and SOG: 7.5 knots, the red line represents AIS messages with COG: 300° and SOG: 7.1 knots, and the green line represents AIS messages with COG: 280° and SOG: 7.5 knots.

In all three papers, trajectories were used to capture the general traffic in the respective case study. The method in Paper I, to define the ship domain, and the method in Paper III, to identify events, both firstly use the trajectories to find candidates and secondly position data to do the analysis. In Paper I the trajectories are interpolated into points every second, and in Paper III, the actual positions are utilised. In Paper II, the interpolated points from Paper I are used to calculate the VCRO value and raw AIS data was used as input to the IWRAP software.

The AIS data used in this research are continuously streamed from various sources and stored as NMEA encoded text (Raymond, 2019) together with a timestamp in text files. The AIS trajectories used in the analysis are stored in an in-house Postgres database with the spatial extension PostGIS. The code for selecting data from the database is written in SQL, whereas the code for analysing the data and generating graphics is written in the programming language Python.

3.2 Revisiting the ship domain

The main scope of Paper I is to revisit the ship domain concept by Fujii and Tanaka (1971) and investigate how different parameters affect the meeting distance. A key concept in this context is the temporospatial distance between ships, i.e. the distance between them with the same timestamps. A ship that passes another ship's path several hours or days later will not affect the behaviour of the first ship. A flowchart of the methodology used in Paper I is shown in Figure 4.

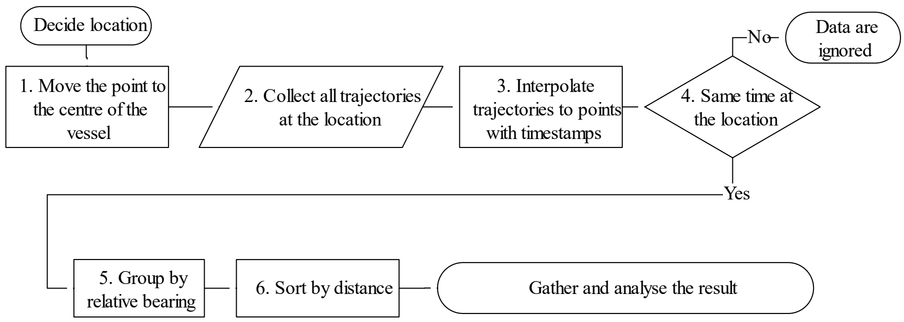

Figure 4. Flowchart of the methodology used in Paper I to determine the ship domain.

In this research, the distance between the ships' centre is investigated, similar to Hansen et al. (2013). So, the first step of the methodology is to relocate the position to the ship centre from the position onboard where the AIS transmitter is located. The next steps in the methodology are to collect all the trajectories at the decided location and interpolate these trajectories into positions every second. Other research, such as Zhang and Meng (2019), interpolated the pairs every 30 seconds and Rawson et al. (2014) interpolated their pairs every 10 seconds. After this operation, records without any other ship closer than 5,000 metres are excluded from the analysis.

The remaining temporospatial pairs were then grouped by bearing and sorted by distance. The closest 5 percent of all meetings were considered to intrude the ship domain, and the rest of the meetings were considered to occur outside of the ship domain. The closest 5 percent was also utilised as a criterion for Gucma and Marcjan (2012) and Cheng et al. (2014). Pietrzykowski and Magaj (2016) used a 7.5 percent limit, and Hansen et al. (2013) used both a 5 percent and 7.5 percent limit. The maximum search distance, which is closely connected to this criterion, was studied in Paper I. In Paper II, the ship domain from Paper I was applied in an existing risk model, the VCRO model by Zhang et al. (2016). In Paper III, the domain was used to identify ships that were unaffected by the presence of other ships while gathering failure event statistics.

3.3 Ship-ship collision

The purpose of Paper II is to investigate how the revisited ship domain influenced an existing model. The VCRO model by Zhang et al. (2016) was selected. The VCRO model was selected since near-misses are important for ship-ship collision assessments, and the equations for the ship domain was well described. In a second step, the result from the VCRO study was compared against the result from the IWRAP software to obtain the accident probability.

A VCRO value is a measurement developed to highlight situations that might be a near-miss. The value can be calculated when two ships are close to each other with Eq. (3.1) (Zhang et al., 2016, 2017):

$$VCRO = \frac{k}{x-l_\theta} y \sum_{n=1}^{n=17} m_n \sin(n \times z) \quad (3.1)$$

in which the constant k is estimated by fitting the minimum error in Eq. (3.3); x is the distance between the ships in nautical miles (nm), l_θ is the length of the ship domain (nm) along the bearing to the second ship, calculated in accordance with Eq. (3.2), y is the relative speed of the ships (knots), z is the phase which is the difference in heading between the ships (degrees), which is positive when ships are approaching each other and negative when they are moving apart, m_n represent the ships' manoeuvrability and can be gathered from a Fourier series expansion (Zhang et al., 2016) as shown in Table 1.

Table 1. Coefficients (m_n) after the Fourier series expansion according to Zhang et al. (2016).

m_1	0.3443	m_5	0.04933	m_9	0.01556	m_{13}	0.001044	m_{17}	-0.01129
m_2	-0.005811	m_6	-0.01347	m_{10}	-0.008126	m_{14}	-0.005202		
m_3	-0.06834	m_7	-0.002292	m_{11}	-0.0009892	m_{15}	0.01056		
m_4	0.01177	m_8	0.01041	m_{12}	0.007698	m_{16}	0.001526		

The coefficients in the Fourier series are based on crossing situations in the Gulf of Finland and were assumed to be valid in Paper II.

$$l_\theta = \left[\frac{1+tan^2\theta}{\frac{1}{S^2}+\frac{tan^2\theta}{R^2}}\right]^{\frac{1}{2}} \quad (3.2)$$

In Eq. (3.2), S and R are the lengths of the half axes of the elliptic ship domain. Zhang et al. (2016) use the Fujii and Tanaka (1971) ellipse, where $S = 1.6 \times L$ (L is the ship length), and $R = 4 \times L$, where both L and x are expressed in nautical miles. The bearing, θ, was counted positively in clockwise fashion from the ships' own heading to the azimuth of the target ship.

Zhang et al. (2017) highlight that one issue with the model by Zhang et al. (2016) is that the ships in the meeting will get different VCRO values depending on the ship lengths. The risk interpretation of the situation may therefore differ onboard the two ships. Zhang et al. (2017) implement a ship domain by Wang et al. (2009) and obtain a mean VCRO value for the situation. In Paper II, the location-specific ship domain was used instead of the ship domain by Wang et al. (2009), in addition to the one from Fujii and Tanaka (1971).

$$\text{Min}\left(\left|E\left(VCRO\left(x_{1nm+l_\theta}\right)\right) - 100\right| + \left|E\left(VCRO(x_{6nm})\right) - 5\right|\right) \quad (3.3)$$

Eq. (3.3) is a combination of Eqs. (24) and (25) by Zhang et al. (2016). It defines that all situations, with a ship at a distance of one nm plus the length of the ship domain, as potentially dangerous and should have a high VCRO value (which is set to 100). All situations with a ship passing at a distance of six nm, are considered safe and should have a low VCRO value (which is set to 5). To obtain this equilibrium, the VCRO value is calculated for all situations in a location with a range of *k* values. This range varies between the different locations; in the case study area outside Gothenburg, *k* values between 35 and 70 were used to find the minimum error, this is illustrated in Figure 5.

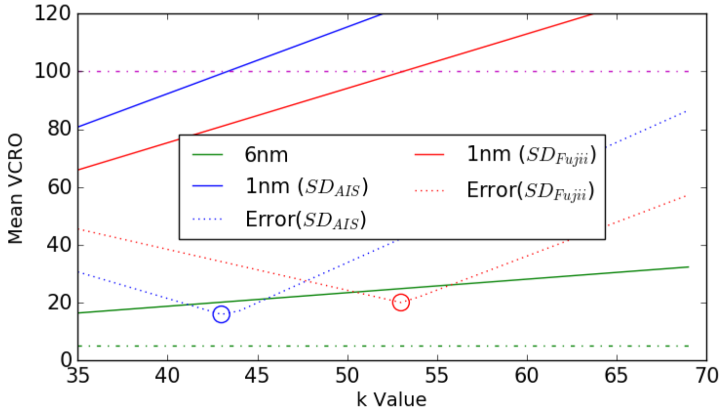

Figure 5. VCRO values for a range of *k* values for SD_{AIS} and SD_{Fujii} at Gothenburg.

With separated l_θ and k values for the different ship domains, it was possible to count the number of meetings that had a maximum VCRO value above 100 for the respective ship domains. A VCRO value above 100 does not state that the ships are at risk of collision. However, it was used in the study to compare the identified candidates, in potential near-miss situations, captured with the two ship domains.

As mentioned earlier, the VCRO model aims to highlight situations that might be a near-miss; however, by default, it does not estimate the probability of ship-ship collision. For this purpose, the IWRAP software was used in Paper II. The output from the IWRAP model is given in terms of incidents per year. However, the number of crossing collision candidates can be calculated as the collision/year divided by the causation factor for crossing candidates. In Paper II, the default value of 1.3×10^{-4} was used (Friis-Hansen et al., 2008).

3.4 Ship-bridge allision

The methodology to obtain the probability of ship-bridge allisions proposed in Paper III consists of several parts. The general idea in the methodology is to obtain local event statistics and simulate these events in a ship manoeuvring simulator to get the probability of ship-bridge allisions. All events that are likely to occur in one year are simulated thousands or millions of times. In these simulations, the input parameters are generated with a Monte Carlo simulation method. Simulation of a single ship's voyage takes approximately two seconds on an Intel Core i7-2600 3.4 GHz processor with 16 GB RAM and 64 Bit architecture. By utilizing multiple cores of the processor (and multiple processors), millions of simulations could be computed in hours.

A major difference between the proposed methodology, compared to existing methodologies based on Eqs (2.1) to (2.3), is that no equation estimates the number of allisions. The number of simulations is calculated by equations, but the number of allisions is given by the simulations. Another major difference is that the methodology includes methods to obtain location-specific failure events, in regard to both duration and frequency. Thirdly, the methodology enables new possibilities to study risk mitigation options. A fourth differentiation from previous research is that only a single ship is simulated in each simulation. This is because the event statistics are gathered from single-ship situations, and it is challenging to model all human decisions that could be made in an autopilot logic.

Apart from the probability of allision, this methodology also enables estimations of the design energy the structure needs to withstand. This is possible since the kinetic energy just prior to the allision is captured for all simulated allisions. Several scripts were used to run and control the simulations, compiling the result and analysing it. Figure 6 is an illustration aiming to show how the different key concepts in Paper III are connected.

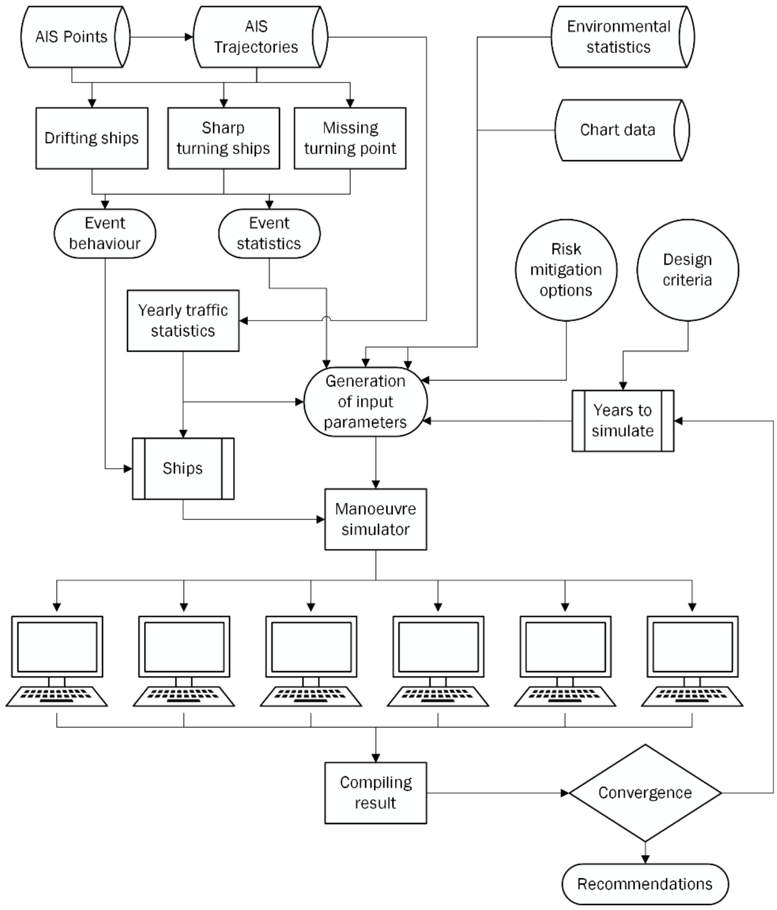

Figure 6. A schematic of the simulation methodology proposed in Paper III.

A central part of the presented methodology is the bridge design criteria. According to Johansen and Askeland (2019), there are different ways to interpret these criteria, and they proposed the use of an FN-curve to better represent both the probability and the consequence. However, to keep it simple, a risk criterion with a threshold of 1×10^{-3} was used in Paper III. It is defined as the bridge should withstand and survive all allisions that have the probability to occur once every 1,000 years.

3.4.1 Event failure statistics

As illustrated in Figure 6, the methodology depends on AIS data to identify three events; *drifting ship*, *sharp turning ship* and *missing turning point*. In short, the methods to identify the three events is carried out in two steps. First is an automatic filter with specified conditions concerning the ship speed, course, etc. applied on all AIS trajectories to obtain event candidates. The original AIS points of the event candidates are manually investigated in a second step.

The ship domain from Paper I was used to exclude ships affected by other ships from the event statistics. Ships affected by other ships are excluded from statistics due to the lack of knowledge concerning if and how the ship was affected by the presence of the other ship. The ship domain from Paper I was chosen since it represents the normal behaviour in the area. Excluding events of ships affected by other ships is an important distinction from the method proposed by Pedersen (1995; 2020), where allision caused by one ship making evasive manoeuvres due to the presence of another ship is an accident category. Multiple ships and collisions between them are also included in the MTS and DMTS simulators.

Similar event categories were presented by Rasmussen et al. (2012), and the methodology to obtain the frequency of the event *missing turning point* is similar to the method used by Rasmussen et al. (2012); (they denote the event “human error”). However, the methodology for obtaining *drifting ship* and *sharp turning ship* differs. Instead of using AIS data to obtain the probability, they used VTS records to obtain the probability (although they denote the events as “loss of propulsion” respective “steering machine failure”).

In total, 153 events were identified in the two areas included in Paper III, the Great Belt VTS and the TSS Bornholmsgat. The frequency for the event *drifting ship* and the event *sharp turning ship* was calculated by dividing the number of events with the number of sailing hours. The event *missing turning point* frequency was calculated by dividing the number of events with the number of ships making the turn. These frequencies, together with the data from Rasmussen et al. (2012), are presented in Table 2.

Table 2. Summary of event frequencies, including the frequencies in a case study presented in Rasmussen et al. (2012).

Event category	Great Belt VTS	TSS Bornholmsgat	Rasmussen et al. (2012)
Drifting ship	0.65×10^{-4}/hour	0.91×10^{-4}/hour	0.6×10^{-4}/hour
Sharp turning ship	0.038×10^{-4}/hour	0.092×10^{-4}/hour	0.1×10^{-4}/hour
Missing turning point	1.55×10^{-4}/turn	2.10×10^{-4}/turn	2.5×10^{-4}/hour

The duration of the identified events was measured between the timestamp of the position report prior to the event being initiated and the timestamp of the position report when the ship was under control, either en route again or safely anchored. In case of *drifting ship* and *sharp turning ship*, the measured time was fitted to a lognormal distribution, and the duration of the event *missing turning point* was fitted to a normal distribution. These distributions are presented in Table 3.

Table 3. Statistical distributions and their parameters for duration of events (time in hours). The parameters correspond to standard deviation, σ, location, ι, scale, λ, and mean value, μ.

Event category	Great Belt VTS	TSS Bornholmsgat	Rasmussen et al. (2012)
Drifting ship	Lognormal σ = 0.71 ι = 0.021 λ = 0.69	Lognormal σ = 0.87 ι = 0.1 λ = 0.97	Weibull σ = 0.5 λ = 0.605
Sharp turning ship	Lognormal: σ = 1.2; ι = 0.06 λ = 0.54		n/a
Missing turning point	Normal μ = 0.064 σ = 0.015	Normal μ = 0.19 σ = 0.047	Less than 0.33

3.4.2 Setting up the simulations and determining the number of years to simulate

The number of simulations for *drifting ship* (i=1) and *sharp turning ship* (i=2) is estimated with Eq. (3.4), and the number of simulations for *missing turning ship* (i=3) is simulated with Eq. (3.5).

$$N_{Sim,i=1,2} = \sum_{j=1}^{15} \sum_{k=1}^{2} P_{ft,i} \times N_{Cat,j,k} \times t_{N,j,k} \times Y_r \tag{3.4}$$

$$N_{Sim,i=3} = \sum_{j=1}^{15} \sum_{k=1}^{2} P_{CSA,i} \times N_{Cat,j,k} \times N_{T,j,k} \times Y_r \tag{3.5}$$

where $N_{Sim,i}$ is the number of simulations for event i, $P_{ft,i}$ is the event probability per hour for the event under study, $N_{Cat,j,k}$ is the estimated number of ships per year for ship type j on a route k in the area, $t_{N,j,k}$ is the average time ship type j sails on the route k, and Y_r is the number of repetitions of one-year's traffic the simulation should represent. $P_{CSA,i}$ is the probability that a ship misses a turn, and $N_{T,j,k}$ is the number of turns the ship j makes on its route k.

Most of the simulations will not result in a ship-bridge allision; however, for those simulations that ended with an allision, the allision energy was calculated according to Eq. (3.6), where M is the ship's displacement, v the ship speed and E is the allision energy. The formula is simplistic; it does not include detailed energy distribution between the ship and bridge, which could be studied by external dynamics simulations (see for example Yu et al., 2016).

$$E = M \times v^2/2 \tag{3.6}$$

The methodology uses the Monte Carlo simulation method to generate the input parameters, and it is important that the results are reproducible. Hence, by defining the random seed, a simulation could be reproduced, and it also ensures that new combinations of random variables are generated (Harris et al., 2020). The number of simulations needed in the set was determined by a criterion defined in this study stating that the difference in allision energy between simulation sets with the same input should not differ more than five percent. If the result of two sets, with the same distribution input, differs more than five percent, the number of repetitions (Y_r) needs to be increased.

The simulator runs were defined in three categories divided into ten simulation sets.

(i) Investigation of the influence from random seeds in the generation of random variables (3 simulation sets, defined as 1A, 1B and 1C).

(ii) A sensitivity study of the parameters (5 simulation sets) defined as:
  2. Increased drifting probability and duration.
  3. Increased probability for sharp turning ships.
  4A. Increased probability and duration for missing turning point.
    4B. Increased probability for missing turning point.
    4C. Increased duration for missing turning point.

(iii) Demonstration of examples of risk mitigation options (2 simulation sets);
  5. 12 knots speed restriction in the Great Belt VTS area.
  6. New layout of the routes, making a longer straight sailing approach to the bridge.

The number of simulations to run in each set is calculated according to Eq. (3.4) and (3.5). Initially, Y_r was set to 10,000 times, and simulations of sets 1A, 1B and 1C were performed. The result of these simulation is presented in Table 4.

Table 4. Results from simulation sets 1A, 1B and 1C with Y_r = 10,000.

Id	Number of simulations	Number of groundings	Number of allisions	Maximum allision energy (MJ)	1,000-year expected allision energy (MJ)
1A	395,770	5,165	59	2,308	1,220
1B	395,770	5,214	67	2,315	1,620
1C	395,770	5,065	56	1,967	1,403

The expected allision energy differed more than 30 percent depending on the random seed, highlighted in Table 4. This variation is primarily caused by the random parameters speed and lateral offset. In simulation set 1B, there were a few more cases of large ships that had unfavourable combinations of high speeds and a big lateral offset compared to 1A and 1C. Y_r was then raised to 100,000 times, and the variation between the random seed became less than 5 percent. The result from all simulation sets is presented in Chapter 4.3.

4 Results

This chapter presents a summary of the appended Papers I to III. It highlights the main achievements and presents a selection of important results from the papers.

4.1 Summary of Paper I – A revisit of the definition of the ship domain

The aim of Paper I is to define which parameters today influence the ship domain. This investigation clarifies the definition of the ship domain and proposes a new method to quantify the size and shape of the domain by using historical ship-ship encounters. The main finding of the paper is that the size of the ship domain is not dependent on the length of the ship, since small and large ships keep a similar meeting distance. The remainder of this subchapter highlights some of the key findings of Paper I.

Ship size

In Paper I, 36 locations all around the Swedish coast and over 600,000 encounters were analysed. Based on this study, it was concluded that the ship domain has the shape of an ellipse, which is similar to previous research (Fujii and Tanaka, 1971; Hansen et al., 2013; Pietrzykowski and Magaj, 2016). The lengths of the half axis in the ellipse were found to be 0.9 nm and 0.45 nm. These are defined in nm, which is a contradiction to Fujii and Tanaka (1971) and Hansen et al. (2013), who defined the ship domain in the unit ship length. This is illustrated in Figure 7, where the ships (both the ship under study (own ship) and the other ship (target ship)) were separated into four length categories.

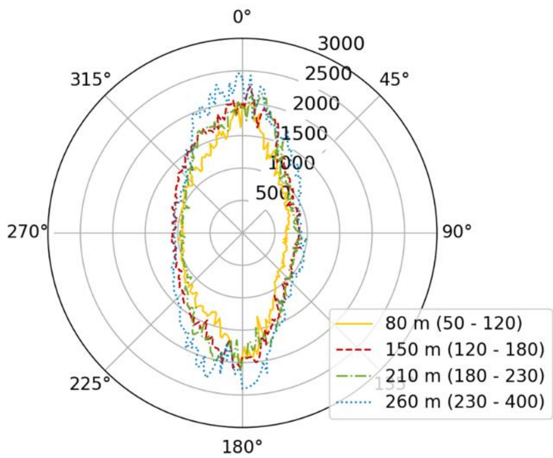

Figure 7. Illustration of the ship domain with different sizes of ships, gathered in the Kattegat sea between Sweden and Denmark.

The ship domain defined by Fujii and Tanaka (1971) increased linearly with the length of the ship. This means their ship domain of a 260 m long vessel would be 3.25 times larger than the ship domain of an 80 m long ship. As illustrated in Figure 7, this is not the case; the ship domain does not increase with the length of the ship.

Geography

It was found in Paper I that one parameter that affects the ship domain is the location; in narrow waterways, the ships are forced to sail closer to each other. In Figure 8 this is exemplified with two locations in open sea: Kattegat – In the T-route and Bornholmsgat – Within the TSS and two locations with restricted depth; and Öresund – East of Ven and Öresund – Drogden channel. Since the length of the ship did not affect the length of the ship domain, ships of all sizes are used for each location. The ship domain in the two locations with open sea are similar, and the ones with restricted waters are narrower.

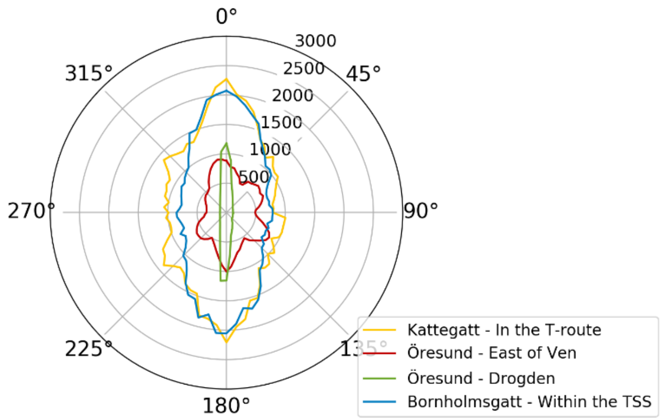

Figure 8. The ship domain in different locations.

The location Öresund – East of Ven has rather dense ferry traffic crossing the main lane, and the ship domain is more circular shaped compared to the more-elliptic-shaped in the Drogden channel. This connects to another finding of Paper I, and it is important to understand that the ship domain could be observed both from the own ship and the target ship, defined as the spectator location.

The spectator location

The spectator view of the shape of the ship domain is different in overtaking situations (elliptic) compared to crossing situation (more circular). However, Figure 9 illustrates that there is one ship domain per ship in an intersection, one for the own ship and one for the target ship. The action of the target ship affects the ship domain the spectator will see while investigating the own ship. In Figure 9, the own ship and four different target ships illustrate how their ship domain affect the resulting ship domain (i.e. the ship domain the spectator will see, while investigating the own ship) in the overtaking and crossing situation.

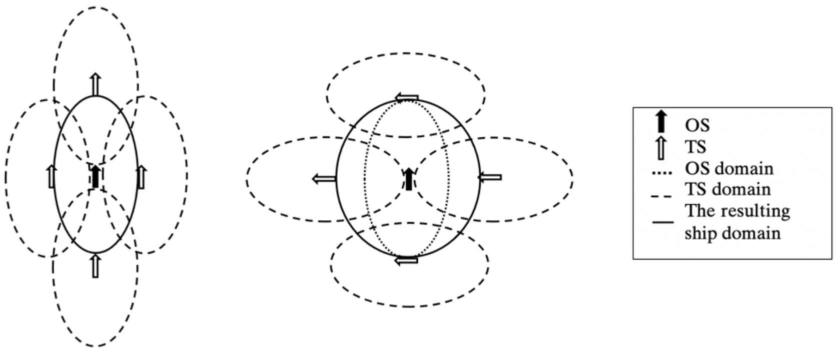

Figure 9. The ship domain in different intersection types.

In the overtaking situation (on the left-hand side in Figure 9), the resulting ship domain has the same size as the own ship's ship domain. However, in the crossing situation, both the own ship and target ships' ship domain affects the resulting ship domain (illustrated on the right-hand side in Figure 9).

The maximum distance to target location

A fourth finding in Paper I is connected to the definition of the ship domain, where the 5 percent closest target ship defines the domain. Even if the paper did not investigate the sensitivity of this definition in detail, the parameter search distance was investigated. Four different "search lengths" were used in a sensitivity study in Paper I, and the result of this study is illustrated in Figure 10.

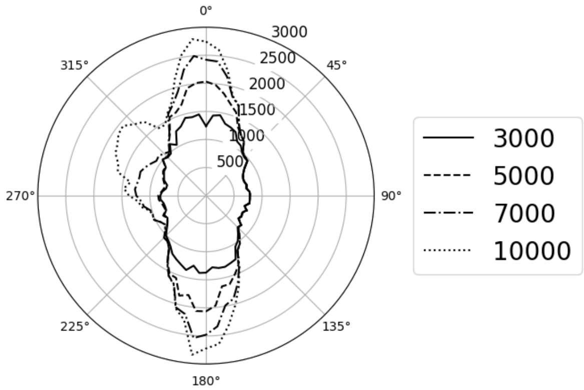

Figure 10. Different maximum distance to target ship.

The figure illustrates that the ship domain increases while the maximum distance to target ship increases. This increase is exemplified with the following example: 5,000-metres distance yields a total of 100 meetings in one sector, and 10,000 metres yields a total of 200 meetings in the same sector. The length of the ship domain, with a 5,000-metres search radius, will get the distance of the 5th meeting since the ship domain is defined by the closest 5 percent. In the example with a 10,000-metres search radius, the ship domain will instead be defined by the 10th meeting distance, with the 5 percent limit. However, the "2.5 percent closest" distance in the 10,000-metres example is the same as the "5 percent closest" distance in the 5,000-metres example. This means the cut-off limit and search radius are connected.

The bulge between 270° and 315° for the 7,000- and 10,000-metres search distance in Figure 10 illustrates the effect when a too large area is included. To limit the amount of unrelated data that clutter the result, it is recommended to use a 5,000-metres search radius.

Concluding remarks

The main finding of Paper I is that according to AIS data, ships tend to keep a similar distance between each other regardless of the ship size. When the ship domain was introduced by Fujii and Tanka (1971), the size was measured in ship length. However, small and large ships tend to meet at a similar distance. They try to keep almost 1 nm in front of them and a 0.5 nm a side free from other ships. This distance is valid in waters with unrestricted depth, and in areas with more restricted depth, the ships pass each other at a much closer distance. Note that the proposed ship domain does not include any considerations for the ship's manoeuvrability or whether it is safe to use this ship domain. The findings from Paper I, regarding the size of the ship domain, are important in other models that assume that the ship domain resembles the normal meeting distances.

4.2 Summary of Paper II – A comparison of two definitions of ship domain for analysing near ship-ship collisions

The purpose of Paper II is to investigate how the revisited ship domain from Paper I influence existing risk models. This is performed by upgrading the ship domain, from Fujii and Tanaka (1971), to that proposed in Paper I, in the VCRO model (Zhang et al., 2016). The VCRO is a temporospatial risk model, which estimates the danger in real-time, but it does not estimate the probability for ship-ship collision. To get the probability of collision, the IWRAP software was used (Engberg, 2017). The result, in terms of the number of identified collision candidates for the case study, is presented in Table 5.

Comparison of results from the VCRO model and the IWRAP software

Table 5 illustrates that the ship domain from Paper I and the ship domain by Fujii and Tanaka (1971) yield a similar number of meetings with high VCRO values. Using the location-specific ship domain solves the issue, highlighted by Zhang et al. (2017), that ships of different sizes obtain different VCRO values in the same situation. The ship domain from Paper I identifies more candidates with high VCRO values in the Gothenburg and Baltic Sea compared to the ship domain by Fujii and Tanaka (1971). The opposite is true in the Anholt location. The VCRO model, with the ship domain based on AIS data from Paper I, classified more overtaking-like meetings with an increased risk compared to when the ship domain by Fujii and Tanaka (1971) was used.

Table 5. Number of collision candidates.

Location	IWRAP collision candidates	Meetings with VCRO values above 100	
		AIS - Ship domain	Fujii - Ship domain
Gothenburg	70	10,139	8,784
Anholt	205	18,898	24,729
Baltic Sea	120	10,811	8,532

The result from the study also shows that the number of collision candidates differs roughly, with a factor 100 between the IWRAP model and the VCRO models. This highlights that the VCRO model captures more situations that could have been a collision candidate situation. This illustrates that the two models have different purposes: IWRAP is designed to calculate the probability of collision, and the VCRO model is designed to find near-miss situations. The VCRO model includes the temporospatial distance between the ships, which enables a real-time assessment of the situation, and IWRAP only includes the spatial distance, which is used for probability analysis.

Concluding remarks

The main finding of Paper II is the VCRO model and the IWRAP software have different pros and cons. The IWRAP model does not include the timestamp from the positions while assessing the probability of collisions. For this reason, the IWRAP model cannot determine if two ships have collided or not. However, IWRAP is designed to use a more extensive dataset to calculate the probability of collision based on many ship meetings. In contrast, the VCRO model is designed to find near-misses between two ships, although it cannot be used to estimate the probability of collision in an area. In short, since the two models have different strengths, they should be used for different purposes.

4.3 Summary of Paper III – A method for risk analysis of ship allisions with stationary infrastructure

The main objective of Paper III is to improve the methodology for estimating the probability of allision. Paper III introduces a new methodology which uses AIS data and a ship manoeuvring simulator to calculate the probabilities for grounding and allision in coastal waters. The methodology is reliant on the event identification methods presented in Chapter 3.4. The main conclusion from Paper III is that the methodology shows a good correlation with the grounding statistics and could be used to estimate the risk of allision. This chapter introduces the main results from Paper III.

The Monte Carlo simulation method described in Chapter 3.4 was used to carry out a large number of runs in the Seaman simulator, including parameter sensitivity analysis. As described in Paper III and Chapter 3.4.2, ten different simulation sets were simulated; the results of these sets are presented in Table 6.

Table 6. Results from all simulation sets with Y_r = 100,000; number of allision accidents caused by D = drifting ship, ST = sharp turning ship, MTP = missing turning point.

Id	Number of simulations	Number of groundings	Number of allisions (D, ST, MTP)	Maximum allision energy (MJ)	1,000-year expected allision energy (MJ)
1A	3,959,282	50,258	710 (376, 85, 249)	3,221	1,667
1B	3,959,282	51,198	722 (385, 97, 240)	4,634	1,601
1C	3,959,282	51,206	730 (395, 87, 248)	2,708	1,605
2	4,221,089	65,516	985 (651, 85, 249)	3,221	1,667
3	3,994,525	54,268	800 (376, 175, 249)	3,221	1,667
4A	5,169,542	1,020,580	27,954 (376, 85, 27,493)	4,822	4,268
4B	5,169,542	60,662	777 (376, 85, 316)	3,221	1,880
4C	3,959,282	748,053	20,606 (376, 85, 20,145)	5,054	4,179
5	3,959,282	32,003	436 (347, 89, 0)	1,030	12
6	3,962,135	50,255	484 (402, 82, 0)	2,258	22

Reproducibility and probability of grounding

The simulation set 1A, 1B and 1C, which uses the same statistics (the failure event frequencies and duration from the Great Belt VTS area), except the random seed, yields a similar result. The minor difference in the result is expected due to the Monte Carlo simulation. These sets prove that the result of the Monte Carlo simulation is reproducible.

The result of simulation sets 1 (A, B and C) also shows that the probability of grounding is 0.51 per year. Since the average number of groundings is 50,887, and the simulations represent one year 100,000 times. A probability of grounding of 0.51 corresponds very well with the accident statistics from the area since five groundings were reported during a ten-year period (IHS Fairplay, 2020).

Sensitivity of the event duration and probability

The result of sensitivity assessment in sets 2, 3 and 4 shows that the methodology is most sensitive to the statistics for the event *missing turning point*. In set 2, both the probability and duration of *drifting ship* were increased, using the statistics from the TSS Bornholmsgat. This led to a 30 percent increase in the number of groundings, but this did not affect the allision energy. A similar result is also found in simulation set 3, where the *sharp turning ship* probability was increased by 50 percent, although the increase in the number of groundings was only a few percentages.

The simulation set with increased probability and duration of the event *missing turning point* 4A differs from the previous sets. The set was for this reason divided into 4B – increased probability and 4C – increased duration. The increase of probability increased the number of groundings with 20 percent and the allision energy with 12 percent. However, the increase of duration (on average from 0.064 hours to 0.19 hours) in set 4C had a major effect of the number of groundings, increased with 1,048 percent, and the allision energy, increased with 250 percent. This has not been studied or highlighted by similar studies within the same research area (e.g. Goerlandt and Kujala, 2011; Rasmussen et al., 2012; van Dorp and Merrick, 2011). Another way to analyse the result is presented in Figure 11, where the allision energy from set 1A is compared with set 4C.

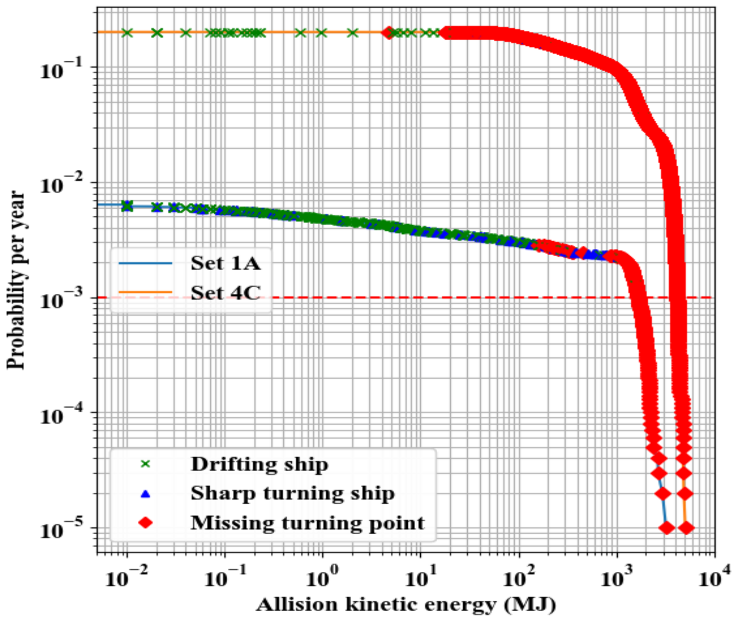

Figure 11. A log-log diagram presenting the probability of allision energy for the simulation sets 1A and 4C (with increased missing turning point duration).

Johansen and Askeland (2019) suggested using an FN-curve as design criteria; this curve has probability and fatalities on the diagram axis. Figure 11 does not contain the number of fatalities, but in future research, the allision energy could be translated to damages to the bridge. This, in combination with usage estimation, could give the number of fatalities.

Mitigation suggestions
The two mitigations, reduction of maximum allowed ship speed and change of navigation path, are examples that illustrate how this methodology could be utilised. As illustrated by simulation sets 5 and 6, they both reduced the expected allision energy approximately 99 percent. It should be noted that the suggested mitigation actions have not been confirmed as realistic measures to be enforced in the area. However, with the methodology presented in Paper III, it is shown that they are worth investigating further.

Figure 11 also shows that the allisions with the highest kinetic energy are caused by ships that miss a turning point, which justifies that this event is more sensitive to an increase of probability and duration compared to the other events. It also explains why the mitigation actions, which removed all allisions caused by the event *missing turning point*, were successful in reducing the allision energy.

The methodology presented in Paper III can be applied either in the planning phase of a new bridge over a waterway or in the assessment of marine traffic situations near existing bridges where the marine traffic may have changed since they were designed and built. The methodology is not limited to ship-bridge allisions; it can also be used to assess the probability of allisions with other infrastructure offshore, or other marine accidents such as ship groundings.

Concluding remarks
The Great Belt VTS area was used in Paper III to verify that the methodology could predict the probability of ship groundings. The methodology included three methods that identified and quantified failure events in terms of frequency and durations. The frequency of these events differs from area to area. However, the frequencies in the Great Belt VTS area were similar to what Rasmussen et al. (2012) reported. After simulating the ship traffic from one year 100,000 times, the number of groundings corresponded well with the accident statistics from the past ten years. It was concluded that the presented methodology can be used to simulate and analyse traffic situation schemes in coastal waterways to calculate the probability that a ship accident will occur. The sensitivity study in the methodology highlights that the duration of the event *missing turning point* is the most sensitive parameter.

One problem with the existing framework for allision risk assessment is that the probability and consequence of the event are often treated separately. The methodology proposed in Paper III reduces this problem. Even though the methodology focuses on the probability, it includes a conservative calculation of the allision energy, and all parameters from the ship needed for structural analysis are stored.

5 Conclusions

The objective of this thesis was to contribute to a safer ship navigation in fairways through the development of numerical models and methods for analysis of what is considered as normal navigation behaviour at sea today and by an analysis of the probability of ship-bridge allisions.

One of the aims of this thesis is to propose a new methodology for defining the ship domain based on current local characteristics. The ship domain was introduced in the early 1970s, and since then, the resemblance of the domain has often been based on the length of the ship. The normal behaviour at sea today was studied in Paper I. With the new definition of the ship domain, based on AIS data, it was concluded that ships tend to keep a similar distance between each other regardless of the ship size. However, as also confirmed by others, the geography affects how closely ships meet. In open water, the distance between ships is larger compared to channels where the meeting distance is smaller.

To improve the analysis of ship-bridge allisions, three types of methods were developed to identify *drifting ship*, *sharp turning ship* and *missing turning point* in Paper III. The events were quantified with respect to frequency and duration. These methods are based on AIS data, which enables the possibility to obtain local event failure statistics wherever there is AIS data available. In this paper, the simulation of failure events was verified with real-world examples to ensure that the simulation replicated the failure events recorded with AIS data.

Paper III proposes a methodology that uses these failure events and AIS data in a ship manoeuvring simulator to estimate the design load on maritime infrastructure. This methodology was applied in the Great Belt VTS area, where one-year traffic was simulated 100,000 times in a Monte Carlo simulation. The simulation methodology was verified with the probability of grounding; it proposed a grounding probability of 0.51 groundings per year, and the reality showed 5 groundings in 10 years. The allision energy was calculated for the allision cases, and from these cases, the 1,000-years design energy was defined, which is used in the bridge design criteria.

Based on the result in Paper III, it is concluded that increased probability and duration of the failure events increase the probability of allision. The probability and, especially, the duration of *missing turning point* had a major impact on the design criteria. However, in the case study, it was also concluded that the probability of the events *drifting ship* and *sharp turning ship* did not affect the design criteria.

Apart from estimation of the design load on maritime infrastructure, the simulation methodology also enables new possibilities to analyse risk mitigation options. In the case study, two different mitigation options were analysed, a reduction of ship speed and a change in traffic pattern. Both options reduced the allision energy by 99 percent.

In summary, this thesis firstly contributes to a better representation of normal behaviour at sea, which is used both in fairway designs and estimations of ship-ship collisions. Secondly, this thesis also contributes to a better understanding of the modelling of probability for ship-bridge allisions. This will support bridge-building engineers who need to consider accidental loads from ship-bridge allision while designing bridges.

6 Future work

Several areas of research and improvements of methodologies together with possible solutions have been identified for future work. In addition, knowledge gaps and possible development paths were established, and some thoughts on future studies are presented below.

Enhancements of the methods connected to the ship domain

The methodology of obtaining the ship domain could be extended to include variables to tune the ship domain for different events. One example is a parameter to alter the ship domain depending on the fairway width. Other parameters where it is recommended to study the extremity and maybe include as a parameter could be:

- Slow versus fast ships.
- Good versus bad weather.
- Daylight versus darkness.

Extending the methodology to include such specific parameters could be interesting in specific cases. To give one example: if the ship domain for fast-going ship is different from the ship domain for other ships, it is necessary to use the correct ship domain while assessing the probability of ship-ship collision for fast-going ships.

Enhancements of the methods connected to the ship-ship collision

In further studies regarding ship-ship collision analysis, it is recommended to connect the ship domain research with the probability of event failure. Such study reveals the connection between the location-specific size of ship domain, the navigational layout and the probability of ship-ship collision. The first step in such study will determine the minimum distance when it is not possible to avoid an accident. Ship-ship collision caused by a failure event that occurs at a greater distance than this could be avoided by actions of the ship without failure. However, to establish this a more advanced study needs to determine a possible set of actions and reaction times. This enhancement could either be done by extending the VCRO model to include the probability of a failure event or extend the simulation methodology in Paper III to include multiple ships and collisions.

Enhancements and extensions of the methods connected to the ship-bridge allisions

Connected to the methodology in Paper III, it is recommended to study failure events in more areas and to improve the methods for event identification. When event statistics are studied in enough areas, it is possible to estimate the statistics for areas that will get a new traffic pattern, e.g. when a bridge have been built or new regulations are put at force. Closely linked to this enhancement, it is also recommended to identify more types of events, and the following are a few examples:

- Ships that turn at the wrong location.
- Ships that set a faulty course at a waypoint.

In the methodology presented in Paper III, there is no reduction in kinetic energy for glancing allisions or for allision against the mast/deckhouse. In future research, it is recommended to connect the methodology in Paper III with a methodology for structural integrity analysis. This extension of the methodology will improve the consequence assessment, making this a better tool for risk assessments. Two recent examples of structural integrity analysis are the simulations of ship deckhouse allision loads on bridge girders by Sha and Amdahl (2019) and the research analysis in both ABAQUS and LS-DYNA for crushing ships with bulbous bow by Storheim et al. (2016). Both describe detailed methodologies for the consequences of an allision. Extending the methodology with methods used by Sha and Amdahl (2019) or Storheim et al. (2016) would improve the consequence analysis to the methodology. With an improved consequence assessment, the methodology can determine what loads the structure should be able to withstand.

Another path for extending the methodology is to include simulations of multiple ships and add both collisions and allisions caused by avoiding another ship as failure modes. This path requires incorporating research with artificial intelligence like Shen et al. (2019), in order for the autopilot to make decisions in complex meeting situations. However, the main “issue” with that type of research today is that it does not include failure events. The algorithms are designed to behave optimally and avoid all collisions; they do not include mechanical failures or human error today. Further, the artificial intelligence does not represent all actions that we as humans could make. Before multiple ships are included in the methodology, there is a need to include a wider range of possible actions that better represent humans’ decisions.

There are other areas where the probability of allision is important, for example, ship-windfarms and ship-quays. The methodology developed in Paper III can easily be adapted to fit these types of allisions.

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